Peter Skands (Lund)

(report on work performed with W. Porod, ITP U. Zürich)

Measuring Neutrino Mixing at LHC?

— How to measure neutrino mixing using only a hadron collider and no water.

LUNDS UNIVERSITET

See also:

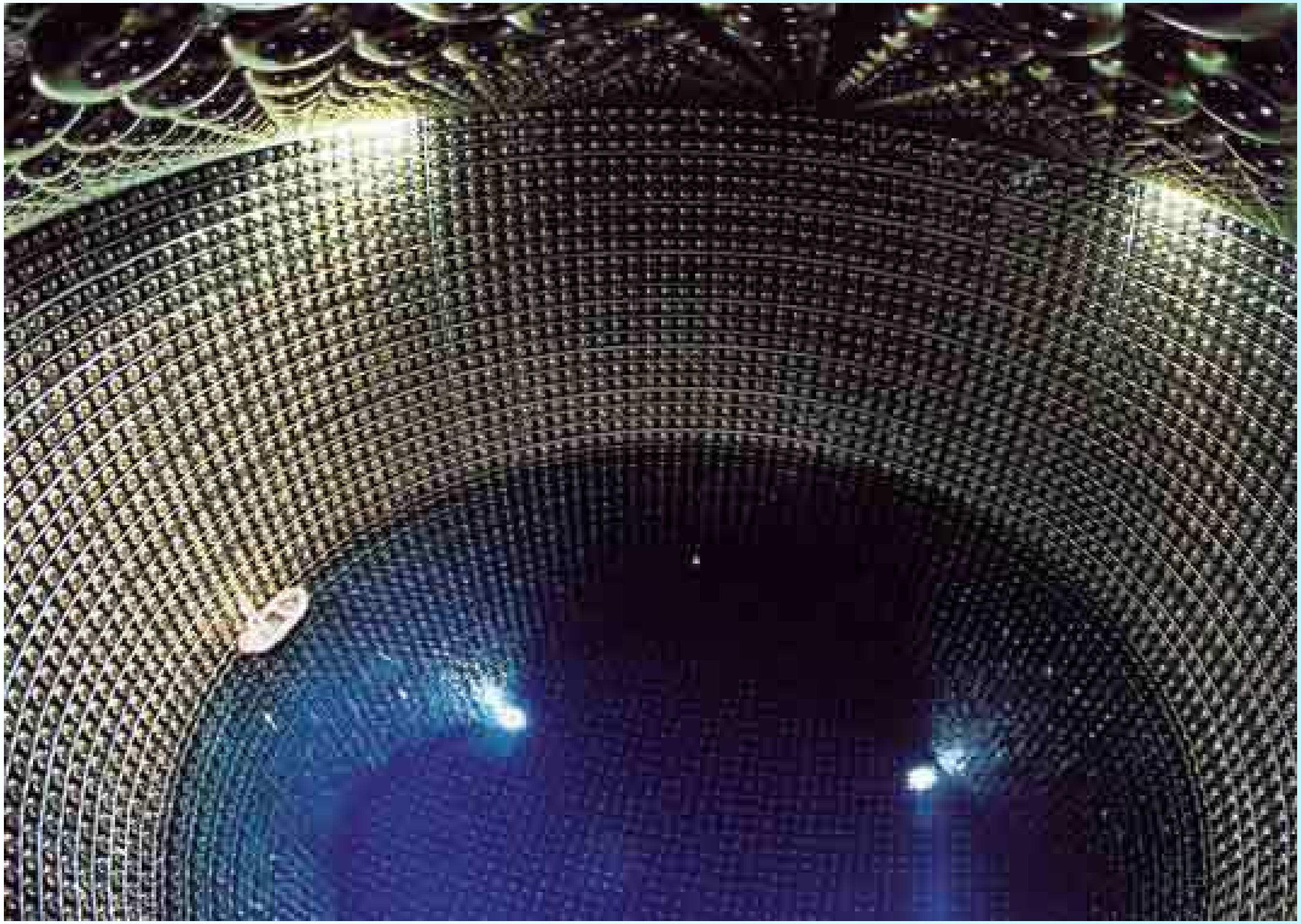
W. Porod+PS, hep-ph/0401077

M. Hirsch+W. Porod, Phys.Rev.D68:115007(2003)

W. Porod+M. Hirsch+J. Romao+J. Valle, Phys.Rev.D63:115004(2001)

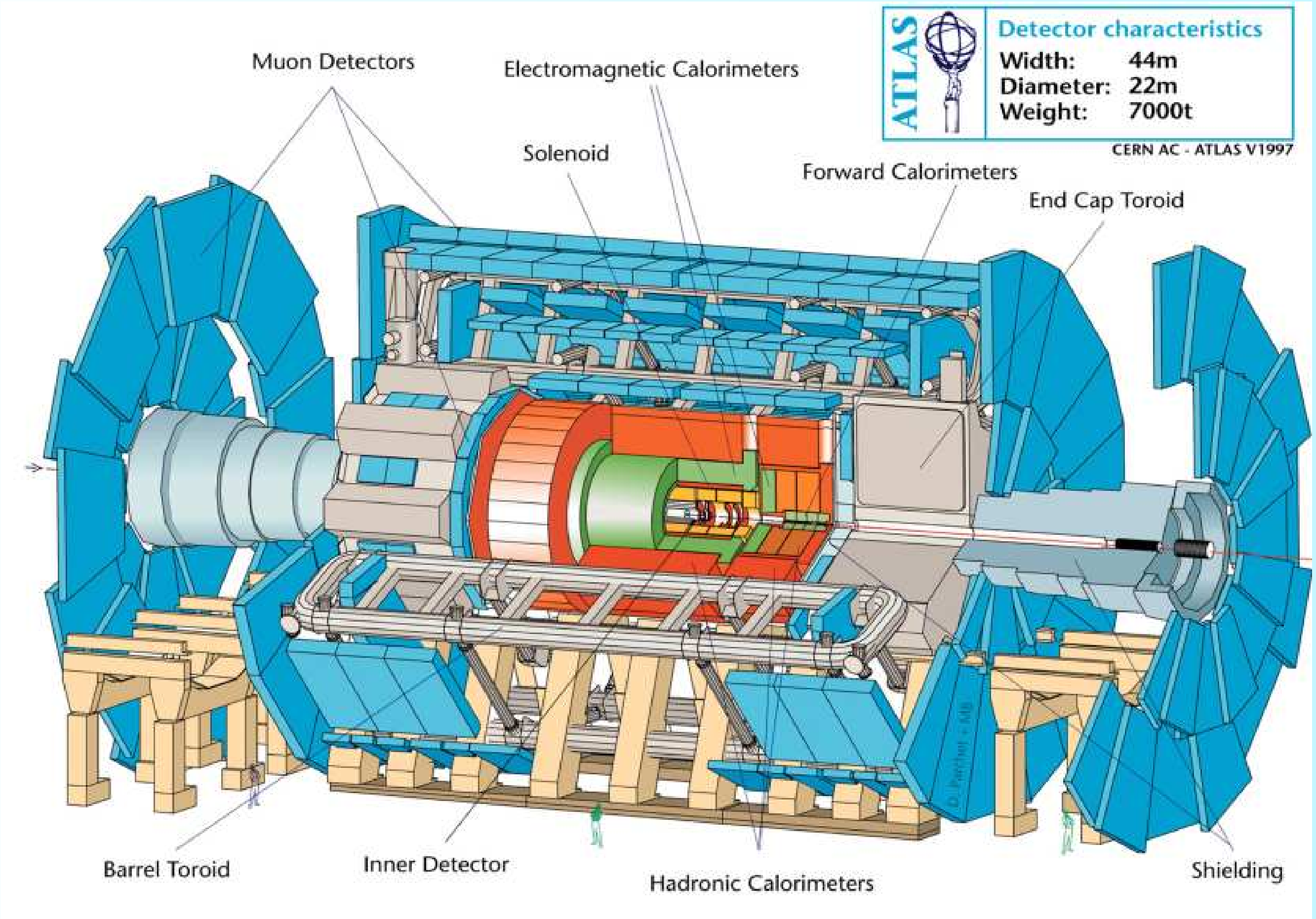
Sanity Check

- This is a detector for neutrino physics.



Sanity Check

- This is not a detector for neutrino physics.



Overview

1. Fast Forward SUSY Intro.
2. R–Parity and R–Parity Violation.
3. R–Parity Violation with Bilinear Terms: a SUSY origin of ν masses?
4. Measuring a ν angle at a hadron collider?

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Supersymmetry.

FAST FORWARD

Presumably more about this in training course tomorrow!

In fast–forward mode, supersymmetry is:

- The only (interesting) way of extending the known space–time symmetries.
- A fundamental relation between fermionic and bosonic degrees of freedom.
- The “super” in superstrings.

TeV–Scale SUSY is popular among BSM theories because:

- It provides an elegant solution to the hierarchy problem.
- It predicts a natural dark matter candidate.
- It paves the way for natural grand unification.
- It is something experimentalists can look for.

Supersymmetry.

FAST FORWARD

SUPERSYMMETRY

For every boson, there is a fermion
For every fermion, there is a boson

6 leptons + 6 quarks — $S=\frac{1}{2}$

photon + $W^{\pm}$ and Z^{0} + gluon — $S=1$

Higgs — $S=0$

Supersymmetry.

SUPERSYMMETRY

For every boson, there is a fermion
For every fermion, there is a boson

6 leptons + 6 quarks		S=$\frac{1}{2}$
2$\times$6 sleptons + 2$\times$6 squarks		S= 0
photon + $W^{\pm}$ and Z^{0} + gluon		S=1
photino + Winos and Zino + gluino		S=$\frac{1}{2}$
Higgs		S=0
Higgsino		S=$\frac{1}{2}$

+ (at least) another Higgs doublet.

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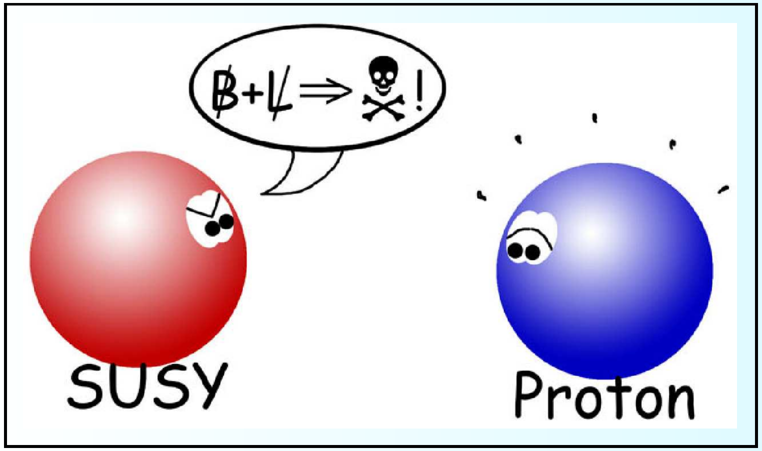
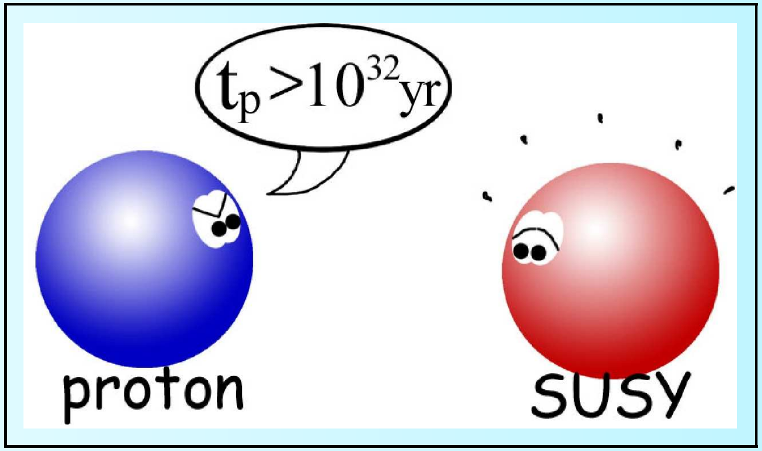
Aberdabei

So SUSY is really popular, but...

in *any* Supersymmetric extension of the Standard Model (SM), the first problem you have to deal with, is how to avoid **rapid proton decay!**





BNV+LNV together is a bad cocktail!

- Write down all (renormalizable) terms consistent with SM gauge invariance and ($N=1$) Supersymmetry $\rightarrow$

$$W_{\mathrm{SUSY}} = W_{\mathrm{MSSM}} + W_{\mathrm{BNV}} + W_{\mathrm{LNV}}$$

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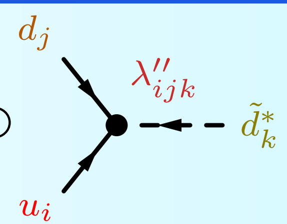
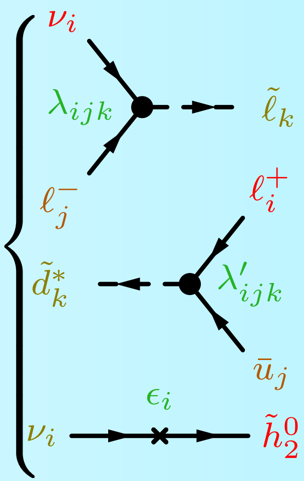
$$W_{\mathrm{SUSY}} = W_{\mathrm{MSSM}} + W_{\mathrm{BNV}} + W_{\mathrm{LNV}}$$

  - $W_{\mathrm{MSSM}} = \boxed{Y^E_{ij} H_1 L_i \bar{E}_j + Y^D_{ij} H_1 Q_i \bar{D}_j + Y^U_{ij} H_2 Q_i \bar{U}_j + \mu H_1 H_2}$ **NOT INTERESTING NOW!**
  - $W_{\mathrm{BNV}} = \boxed{\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k} \supset$ 

  - $W_{\mathrm{LNV}} = \boxed{\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \epsilon_i L_i H_2} \supset$ 

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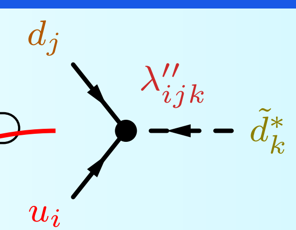
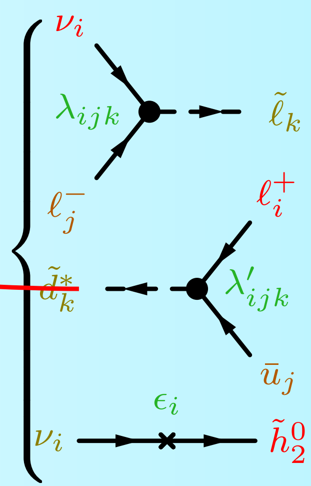
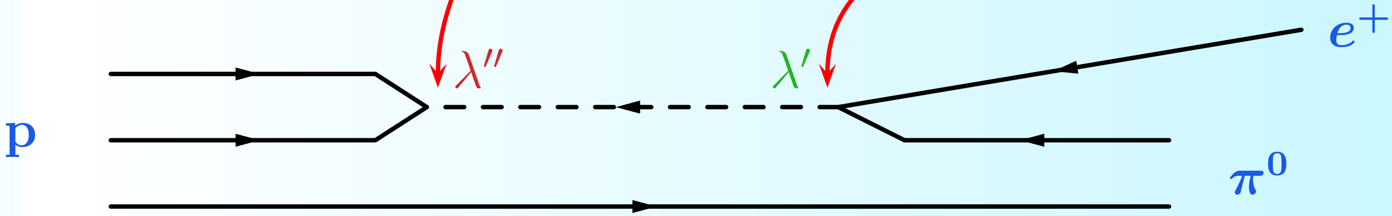
  - $W_{\mathrm{BNV}} = \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k \supset$



  - $W_{\mathrm{LNV}} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \epsilon_i L_i H_2 \supset$





- $\rightarrow$ fast proton decay $\propto \frac{|\lambda'||\lambda''|}{M^2_{\mathrm{SUSY}}} \overset{M_{\mathrm{SUSY}}\sim 1\mathrm{TeV}}{\Longrightarrow} |\lambda'||\lambda''| \lesssim 10^{-30}$.

What can be done?

- Start with naive, simple guesses:

1. Lepton Number is conserved?
2. Baryon Number is conserved?
3. Both are conserved (R-parity $= (-1)^{L+3B+2S}$)?

What can be done?

- Start with naive, simple guesses:
  1. Lepton Number is conserved?
  2. Baryon Number is conserved?
  3. Both are conserved (R-parity $= (-1)^{L+3B+2S}$)?

- R-parity has interesting consequences:

  SM particles have $R = +1$ and SUSY ones $R = -1$
  $\to$ sparticles are born and killed by the pair ...
  so sparticles from Big Bang decayed to “LSP” are still around?
  $\to$ solution to dark matter problem in cosmology?

- But no deep theoretical motivation...

Simple guesses ain't so bad!

What can we say about the symmetry we're looking for?

- Only discrete gauge symmetries are absolutely stable.
- But you can find discretized versions of gauge symmetries which reduce to both R-parity as well as symmetries equivalent to Baryon and Lepton number conservation.
- $\Longrightarrow$ Again no clear preference for one or the other.

What about Beyond-the-MSSM contributions?

- R–parity does not forbid $D > 4$ proton decay.
- Anyway, all this was just to make the case...

All possibilities should be considered!

R conservation vs R violation.

$$W_{\mathrm{SUSY}} = W_{\mathrm{MSSM}} (+W_{\mathrm{BNV}} + W_{\mathrm{LNV}})$$

- $W_{\mathrm{MSSM}} = \boxed{Y^E_{ij} H_1 L_i \bar{E}_j + Y^D_{ij} H_1 Q_i \bar{D}_j + Y^U_{ij} H_2 Q_i \bar{U}_j - \mu H_1 H_2}$

  Conserves $R \to$ only allows sparticles to be produced in pairs and does not mediate LSP decay.

- Signature is missing (transverse) energy from escaping LSP's.

- At the LHC, squark and gluino pair production will dominate over most of parameter space.

- Typically, squarks and gluinos are among the heavier sparticles, hence other typical features are multiple jets and/or leptons which are split off in a chain of decays to lighter and lighter sparticles, ending with the (stable) LSP.

- Escaping LSP $\to$ tricky mass reconstruction (use edges).

Trilinear Lepton Number Violation

$$W_{\rm SUSY} = W_{\rm MSSM} + W_{\rm LNV}$$

- $W_{\rm LNV} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \epsilon_i L_i H_2$ LATER!

  "LLE" ("LQD") allows single slepton production at a linear collider (hadron collider). "LQD" also allows resonant squark/slepton production at an ep collider.

- Rich phenomenology. With just 2- and 3-body decays of sparticles to particles, more than 1200 new decay chanels!

LLE(λ):

- $\tilde{e}^-_j \to \bar{\nu}_i \ell^-_k,\ \nu_k \ell^-_i$
- $\tilde{\nu}_j \to \ell^+_i \ell^-_k$
- $\tilde{\chi}^0_n \to \bar{\nu}_i \ell^+_j \ell^-_k,\ \nu_i \ell^-_j \ell^+_k$
- $\tilde{\chi}^+_n \to \ell^+_i \ell^+_j \ell^-_k$
- $\tilde{\chi}^+_n \to \bar{\nu}_i \ell^+_j \nu_k,\ \nu_i \nu_j \ell^+_k$

LQD(λ'):

- $\tilde{e}^-_i \to \bar{u}_j d_k$
- $\tilde{\nu}_i \to \bar{d}_j d_k$
- $\tilde{u}_j \to e^+_i d_k$
- $\tilde{d}_k \to \nu_i d_j,\ \bar{\nu}_j d_i,\ \ell^-_i u_j$
- $\tilde{\chi}^0_n \to \bar{\nu}_i \bar{d}_j d_k,\ \ell^+ \bar{u}_j d_k,\ + \text{c.c.}$
- $\tilde{\chi}^+_n \to \bar{\nu}_i \bar{d}_j u_k,\ \nu_i \bar{d}_k u_j$
- $\tilde{\chi}^+_n \to \ell^+_i \bar{u}_j u_k,\ \ell^+_i \bar{d}_j d_k$

HERWIG: **P.Richardson,hep-ph/0101105**
PYTHIA: **PS,Eur.Phys.J.C23:173(2002)**

Trilinear Baryon Number Violation

$$W_{\rm SUSY} = W_{\rm MSSM} + W_{\rm BNV}$$

- $W_{\rm BNV} = \boxed{\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k}$

  "UDD", violates Baryon Number. Allows single (resonant) squark production from qq initial state. Allows 2-body decays of squarks to quarks and 3-body decays of gauginos to quarks.

UDD (λ''):

- $\tilde{d}_j \to \bar{u}_i\bar{d}_k$
- $\tilde{u}_i \to \bar{d}_j\bar{d}_k$

- $\tilde{\chi}^0_n \to u_i d_j d_k,\ + \mathrm{c.c.}$
- $\tilde{\chi}^+_n \to u_i u_j d_k,\ \bar{d}_i\bar{d}_j\bar{d}_k$
- $\tilde{g} \to u_i d_j d_k,\ + \mathrm{c.c.}$

HERWIG: **P. Richardson,hep-ph/0101105**

PYTHIA: **T. Sjöstrand+PS, Nucl.Phys.B659:243(2003)**

- NB: Unique colour structures $\to$ new colour topologies not adressed by standard fragmentation schemes. Detailed dynamical modelling so far developed only for string fragmentation (implemented in PYTHIA).

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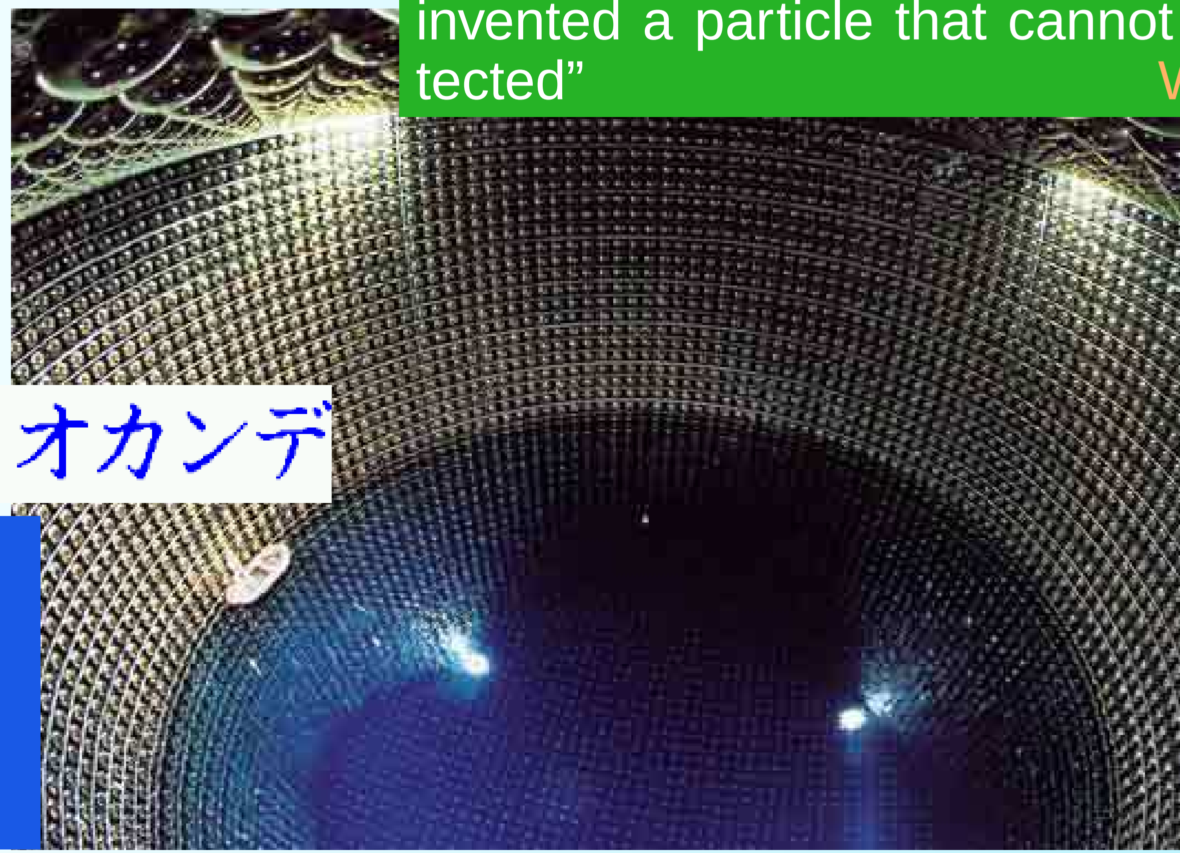
Neutrino Summary

Great surprise:

“I have done a terrible thing, I have invented a particle that cannot be detected” W. Pauli



スーパーカミオカンデ

Masatoshi Koshiba

Raymond Davis Jr.

Nobel prize 2002: Neutrinos have mass!

Neutrino Summary

Neutrino sector: a window to physics beyond SM?

1. Too few ν_μ from atmosphere, can be explained by oscillations into ν_τ: $\Delta m^2_{\mathrm{atm}} = m_3^2 - m_2^2 \sim 10^{-3} - 10^{-2}\,\mathrm{eV}^2$
2. Too few ν_{e} from Sun, can be explained by oscillations into ν_μ: $\Delta m^2_{\mathrm{sol}} = m_2^2 - m_1^2 \sim 10^{-5} - 10^{-4}\,\mathrm{eV}^2$
3. Bi-maximal mixing pattern: θ_{23} large, θ_{12} large, and θ_{13} small.

Explanations generally look like this:

$$\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$$

Neutrino Masses

$$\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$$

m: Dirac mass. Electroweak scale?

M: Majorana mass. High scale?

$$\lambda_\pm = \tfrac{1}{2}M^2 \pm \tfrac{1}{2}\sqrt{M^2+4m^2} \sim \begin{cases} -m^2/M & = & m_\nu \\ M + m^2/M & \gtrsim & 10^9\,\text{GeV} \end{cases}$$

$\hookrightarrow$ No fun for high energy colliders...

An alternative possibility could be M of order M_Z, with m thus being rather small...

$\hookrightarrow$ Testable at high energy colliders...

Bilinear R–violation

$$W_{\mathrm{SUSY}} = W_{\mathrm{MSSM}} + \epsilon_i L_i H_2$$

(Occurs e.g. when R–parity is broken spontaneously)

For us, the important consequences are:

- $\boxed{\text{EW symmetry is broken by Higgs } \textit{and} \text{ sneutrino vev's,}}$

  $\langle \nu_i \rangle = v_i$ (i.e. $m_W^2 = \frac{1}{4} g^2 (v_d^2 + v_u^2 + v_1^2 + v_2^2 + v_3^2)$).

- $\boxed{\text{Neutrinos mix with neutralinos} \rightarrow 7 \times 7 \text{ mixing:}}$

In block form: $M_N = \begin{pmatrix} 0 & m_{(3\times4)} \\ m^T{}_{(4\times3)} & M_{(4\times4)} \end{pmatrix}$

Bilinear R–Violation

Determining the masses:

- Find diagonalizing matrix: $N^* M_N N^{-1} = \mathrm{diag}(m_{\nu_i}, m_{\tilde{\chi}^0_j})$.
- First transform M_N to block-diagonal:

$$N^* M_N N^{-1} = \tilde{N}^* \begin{pmatrix} m_{\mathrm{eff}} & 0 \\ 0 & M_{\tilde{\chi}^0} \end{pmatrix} \tilde{N}^{-1} \ ; \ \tilde{N} = \begin{pmatrix} V_\nu^\dagger & 0 \\ 0 & N_{\tilde{\chi}^0} \end{pmatrix}$$

- The matrix m_{eff} is projective, looks like:

$$m_{\mathrm{eff}} = \frac{M_1 g^2 + M_2 g'^2}{4\det(M_{\tilde{\chi}^0})} \begin{pmatrix} \Lambda_e^2 & \Lambda_e \Lambda_\mu & \Lambda_e \Lambda_\tau \\ \Lambda_e \Lambda_\mu & \Lambda_\mu^2 & \Lambda_\mu \Lambda_\tau \\ \Lambda_e \Lambda_\tau & \Lambda_\mu \Lambda_\tau & \Lambda_\tau^2 \end{pmatrix}$$

$$\boxed{\Lambda_i = \mu v_i + v_d \epsilon_i}$$

Bilinear R–Violation

So only 1 non-zero eigenvalue in $m_{\rm eff}$!

- $N^*_{\tilde{\chi}^0} M_{\tilde{\chi}^0} N^\dagger_{\tilde{\chi}^0} = \mathrm{diag}(m_{\tilde{\chi}^0_i})$
- $V_\nu^T m_{\rm eff} V_\nu = \mathrm{diag}(0,0,m_\nu)$; $m_\nu = \mathrm{Tr}(m_{\rm eff}) \propto \Lambda^i \Lambda_i$

$\rightarrow$ 1 neutrino becomes massive at tree level.
(Remaining neutrinos acquire mass at 1 loop).

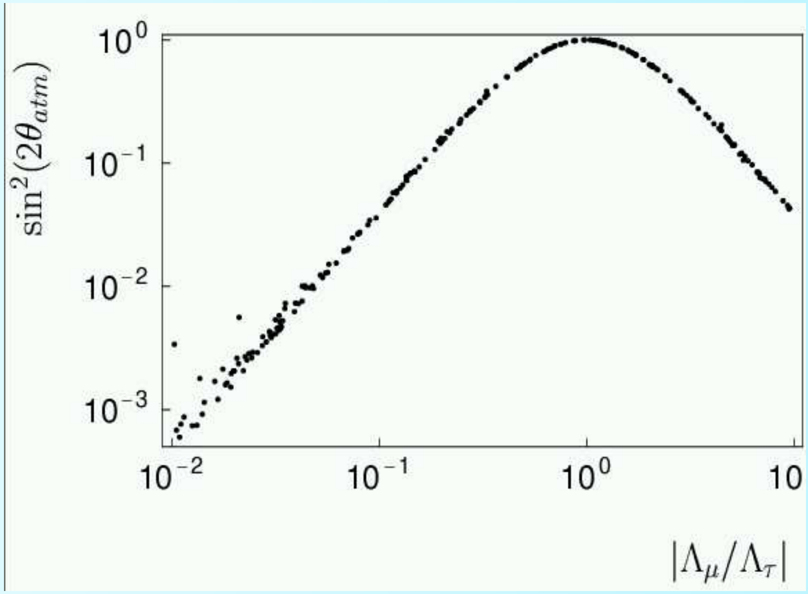
- $$V_\nu = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & -\sin\theta_{23} \\ 0 & \sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & -\sin\theta_{13} \\ 0 & 1 & 0 \\ \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}$$

- NOTE: $\hookrightarrow$ $\tan\theta_{13} = \frac{\Lambda_e}{\sqrt{\Lambda_\mu^2+\Lambda_\tau^2}}$; $\tan\theta_{23} = -\frac{\Lambda_\mu}{\Lambda_\tau}$.

Bilinear R–Violation

Details depend on the particular SUSY scenario, but the general results are:

- The tree-level mass m_ν generates the atmospheric mass scale.
- The loop-induced (=small) corrections generate the Solar mass scale ($\rightarrow$ hierarchical mass pattern).
- With $\Lambda_e \ll \Lambda_\mu \sim \Lambda_\tau$, the bi–maximal mixing can be accomodated.



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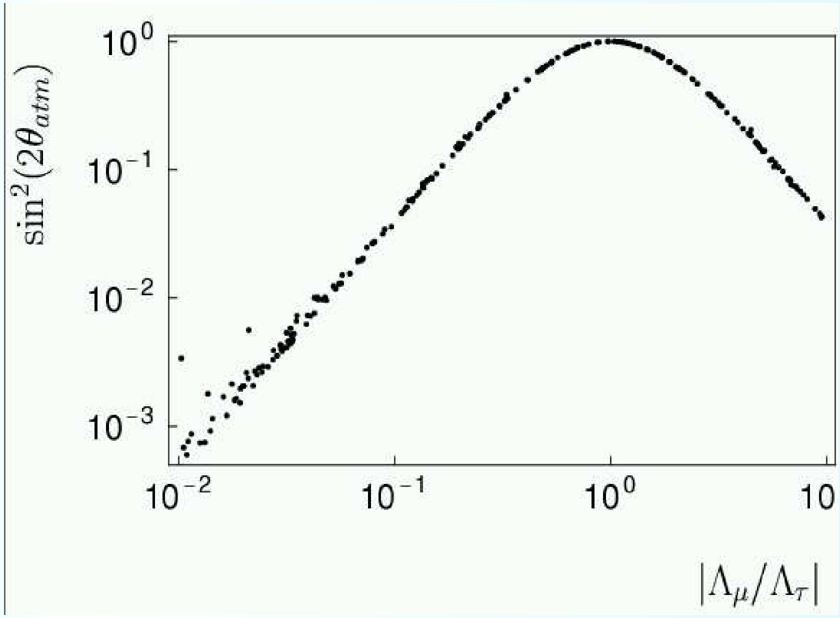
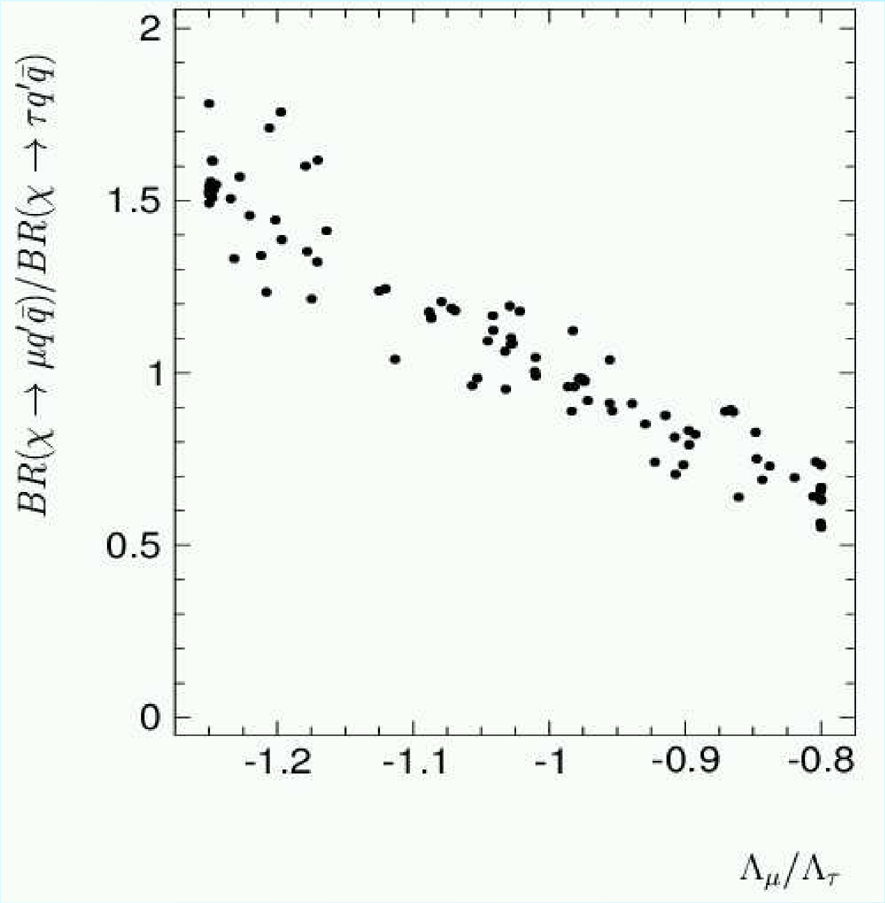
Measuring a ν angle...





- BRPV couplings also responsible for LSP decay.
- $\to$ Ratio of $\tilde{\chi}_1^0$ semileptonic branching ratios is strongly correlated with Λ_i/Λ_j!

Measuring a ν angle...

$\rightarrow$ model of SUSY origin of ν mass can be checked by "measuring" $\theta_{\rm atm}$ at a hadron collider:

$$\tan^2\theta_{\rm atm} \simeq \left|\frac{\Lambda_\mu}{\Lambda_\tau}\right|^2 \simeq \frac{BR(\tilde{\chi}^0_1 \to \mu^\pm \mathrm{W}^\mp)}{BR(\tilde{\chi}^0_1 \to \tau^\pm \mathrm{W}^\mp)}$$

Note: this prediction is independent of the R–conserving MSSM parameters.

To illustrate method, we have investigated a specific example, based on the SPS1a mSUGRA point.
(using SPHENO 2.2 together with PYTHIA 6.3, and SLHA interface to pass parameters)

The R–Violating parameters are (in MeV):

$$\epsilon_i = (43, 100, 10) \qquad v_i = (-2.9, -6.7, -0.5)$$

(chosen to fit neutrino data)

Measuring a ν angle...

Total SUSY cross section for SPS1a: $\sigma_{\mathrm{SUSY}} \sim 41\mathrm{pb}$.

Some shortcuts:

- Detector resolution and hadronization effects are ignored

The "detector":

- Calorimeter: $|\eta| < 4.9$. Inner detector: $|\eta| < 2.5$.
- Electrons ($|\eta| < 2.5$, $\mathrm{p}_\perp > 5\,$GeV, $\varepsilon = 75\%$)
- Muons ($|\eta| < 2.5$, $\mathrm{p}_\perp > 6\,$GeV, $\varepsilon = 95\%$)
- Taus ($|\eta| < 2.5$, $\mathrm{p}_\perp > 20\,$GeV, $\varepsilon_{3-\mathrm{prong}} = 85\%$)
- Vertex resolution: 20μ transverse and 0.5mm longitudinal.
- "Triggers": 4j100, 2j100+e20/mu20, j100+2(e20/mu20).

Measuring a ν angle...

Events characterized by:

- Since $\not{R}$–Violating parameters are small, the only real deviation from MSSM phenomenology is LSP decay.
- $\rightarrow$ pair production of squarks/gluinos dominate, with cascades down to LSP, which subsequently decays through LNV.
- Also due to smallness of LNV parameters, LSP is long–lived. Decay length here is $c\tau = 0.5$mm.
- $\rightarrow$ very clean signature: 2 reconstructed detached vertices in fair fraction of signal events (define vertex reconstruction ellipsoid = 5 times resolution and reject tracks that intersect it).

100 fb^{-1} of data: ~ 10000 reconstructed $\tilde{\chi}^0_1 \rightarrow \mu\mathrm{W} \rightarrow \mu\mathrm{q}\overline{\mathrm{q}}'$ decays.
~ 1500 reconstructed $\tilde{\chi}^0_1 \rightarrow \tau\mathrm{W} \rightarrow \tau_{3-\mathrm{prong}}\mathrm{q}\overline{\mathrm{q}}'$ decays.

$\rightarrow$ precision on $\tan^2\theta_{\mathrm{atm}}$ is $\sim$ couple of percent

Summary & Conclusion

- R–parity: conserved or violated?
  Nobody knows...
- Possible sources of RPV:
  UDD, LLE, LQD, and Bilinear.
- Bilinear RPV has interesting consequences:

Sneutrinos play rôle of extra Higgses and acquire vevs.

Neutrinos mix with Neutralinos.

A "low-scale" seesaw mechanism results, whereby neutrinos become massive.

Models consistent with neutrino data give predictions which can be tested at hadron colliders.

So all we can really say is:

- This may not seem to be a detector for neutrino physics...